THE EFFECT OF ARCHITECTURAL CONFIGURATIONS ON THE BIOLOGICAL LIGHT RESPONSE IN RESIDENTIAL BUILDINGS

Greenhouse project in Malmö

Maha Mohamed Shalaby

Master Thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University
**Lund University**
Lund University, with eight faculties and a number of research centers and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö and Helsingborg. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

**Master Programme in Energy-efficient and Environmental Building Design**
This international programme provides knowledge, skills and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants’ behavior and needs, their health and comfort as well as the overall economy.

The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

Examiner: Thorbjörn Laike (Environmental Psychology)
Supervisor: Marie-Claude Dubois (Energy and Building Design)

**Keywords:** Circadian light, non-visual effects, alertness, design configurations

Thesis: EEBD–16/13
Abstract

Daylight has beneficial psychological and health effects that range from enhanced alertness, mood improvements, increased productivity, and well-being. Recently, the interest in non-visual (also called biological) effect of light has increased substantially. Yet, a limited number of research has investigated the non-visual effects of light in Nordic climates.

The aim of this thesis is to assess the effect of changing the building configuration on the average Biological Light Response (BLR) that would also translate to a proxy for alertness. This research implements a simulation methodology to simulate the BLR on a residential building located in Malmö Sweden. The building was parametrically modelled using Grasshopper plugin in Rhino, while Honeybee, Ladybug, and Lark plugins for Grasshopper were used to develop the BLR simulation workflow.

In the BLR simulation method, four days (two equinoxes and solstices) were simulated with their respective sky conditions for an east- and a west-facing apartment. The simulation considered three CIE sky conditions (overcast, intermediate, and clear) with their corresponding Correlated Colour Temperature (CCT).

The results of the simulation in circadian illuminance were compared to minimum and maximum thresholds, indicating the required illuminance to reach 0% and 100% BLR respectively. The BLR percentage was then calculated indicating the average alertness level reached in the space.

The simulation results of the base case showed that only March and June days reached an average BLR near the set threshold (75% in this case based on previous research). The total average of the four days was approximately 50%. To improve the BLR of current building design, several parameters in the building were varied, and the best configurations were the ones without the balcony and sunspace, as these elements obstruct glazing areas.

In conclusion, the BLR simulation workflow enabled a sound evaluation of the non-visual effects of daylight, paving the way for architects to consider the wellbeing aspect related to daylight during the early design stages.
Acknowledgements

I would like to thank the Swedish Institute for granting me a scholarship to study my masters degree in Sweden.

Thanks to Sarith Subramaniam, PhD student at Penn state university for his constant support in the thesis in the Grasshopper section for providing a Grasshopper script for the sky clearance index based on the research paper (Perez, et al., 1990).

I would also like to thank my supervisor, Marie-Claude Dubois for her constant support in the entire master program, and Ayman Wagdy as assistant supervisor for his support during the thesis.

To my family, my dad, my mom, my sister and my brother, thank you for always pushing me, and getting out the best in me.
**Terminology**

Scotopic: Related to vision in dim light with dark-adapted eyes which involves only the retinal rods as light receptors.

Daysim: Validated, RADIANCE-based daylighting analysis software that models the annual amount of daylight in and around buildings. (Daysim, 2016)

Luminous flux: Energy per unit time (dQ/dt) that is radiated from a source in the visible wavelengths. The unit for measurement of luminous flux is lumen. (C.R.Nave, 2016)

Luminous efficiency function: Eye sensitivity to different wavelengths of the visible part of the spectrum. The Photopic Luminous efficiency function was a standard curve set by the CIE. (Rea, 2013)

Luminous efficacy: Light source’s lumen value against its energy consumption. It is a measure of how good a light source produces light in comparison to its energy consumption. (Glamox, 2016)

Non imaging optics: Branch of optics concerned with the optimal transfer of light radiation between a source and a target.
# Table of contents

Abstract................................................................................................................................................. 1  
Acknowledgements................................................................................................................................. 2  
Terminology.............................................................................................................................................. 3  
1. Introduction .......................................................................................................................................... 8  
   1.1 Aims and Objectives: ...................................................................................................................... 9  
2 Literature review ................................................................................................................................. 10  
   2.1 Photobiology, and daylight in architecture ................................................................................... 10  
      2.1.1 Circadian rhythm and its effect on human health (Biological Light 
            Response) ................................................................................................................................. 11  
      2.1.2 Findings from photobiology .................................................................................................. 13  
   2.2 Methods examining non-visual effect of light ................................................................................ 19  
   2.3 Modelling circadian illuminance ................................................................................................. 22  
      2.3.1 Current software for daylight simulation .............................................................................. 22  
      2.3.2 Limitations of current software ............................................................................................ 24  
3 Method ............................................................................................................................................... 25  
   3.1 Context ........................................................................................................................................... 25  
   3.2 Building information ..................................................................................................................... 25  
   3.3 Building plan .................................................................................................................................. 26  
   3.4 Analyzed spaces ............................................................................................................................. 27  
   3.5 Computer simulations method ...................................................................................................... 28  
      3.5.1 Introducing Lark and its link with Ladybug and Honeybee ..................................................... 28  
      3.5.2 Simulation input ...................................................................................................................... 32  
      3.5.3 Running simulations, and documenting output ....................................................................... 38  
      3.5.4 Parametric simulation ............................................................................................................ 41  
      3.5.5 Calculating the Biological Light response ............................................................................. 45  
      3.5.6 Reading the output .................................................................................................................. 48  
      3.5.7 Results representation in plan .............................................................................................. 48  
4 Results .............................................................................................................................................. 50  
   4.1 Base case ....................................................................................................................................... 50  
   4.2 Parametric simulations .................................................................................................................. 61  
      4.2.1 Part1 .................................................................................................................................. 61
4.2.2 Part 2 .......................................................................................... 62
4.2.3 Part 3 .......................................................................................... 65

5 Discussion .......................................................................................... 68
5.1 Base case ....................................................................................... 68
5.2 Parametric simulations .................................................................... 69
  5.2.1 Part 1 ....................................................................................... 69
  5.2.2 Part 2 ....................................................................................... 69
  5.2.3 Part 3 ....................................................................................... 69

6 Conclusion .......................................................................................... 71

7 Summary ........................................................................................... 73

8 References .......................................................................................... 74

9 Appendix A .......................................................................................... 79

10 Appendix B .......................................................................................... 80

11 Appendix C .......................................................................................... 84

12 Appendix D .......................................................................................... 85
# Table of Figures

Figure 1 Brain centers for visual and non-visual responses ........................................ 12  
Figure 2 Daily hormonal cycle (Volf, 2013) ..................................................................... 13  
Figure 3 Photopic (V(λ)), & circadian (C(λ)) luminous efficiency function, & SPD of different CIE illuminants .......................................................... 14  
Figure 4 Photopic and circadian luminous efficacy (lm/Watt) .......................................... 15  
Figure 5 Relative sensitivity of Photopic and circadian luminous efficiency functions ...... 16  
Figure 6 The photopic and the three cones luminous efficiency functions ...................... 16  
Figure 7 Different circadian luminous efficiency functions ........................................... 17  
Figure 8 ‘Gall’ function (left) & ‘Rea’ function (right) .................................................... 18  
Figure 9 Monochromatic and polychromatic functions by Rea .................................... 18  
Figure 10 Daylight coefficient method ........................................................................... 22  
Figure 11 Backward raytracing technique ...................................................................... 23  
Figure 12 Link between different software and simulation engines ................................. 24  
Figure 13 Building with surrounding context .................................................................. 25  
Figure 14 Analyzed floors in multistory building ............................................................. 26  
Figure 15 East, west and south apartments ..................................................................... 26  
Figure 16 Analyzed spaces in the west apartment (left), full apartment plan (right) ......... 27  
Figure 17 Complete method ......................................................................................... 28  
Figure 18 Sky file without (top) and with (bottom) color information ......................... 29  
Figure 19 Ladybug, Honeybee, & Lark ......................................................................... 30  
Figure 20 Deriving R,G,B components from V(λ) ......................................................... 31  
Figure 21 Deriving the intermediate and clear sky clearance index ................................ 33  
Figure 22 Sky condition for the four months ................................................................ 34  
Figure 23 Sky spectral power distribution for clear skies (top) intermediate (middle), and overcast (bottom) ................................................................. 35  
Figure 24 Overcast sky at 5 am (left) Intermediate sky at 12 am (middle) Clear sky at 7 pm (right) with color ............................................................... 36  
Figure 25 Overcast sky at 5 am (left) Intermediate sky at 12 am (middle) Clear sky at 7 pm (right) greyscale ................................................................. 36  
Figure 26 Position points and analysis directions ........................................................... 37  
Figure 27 Animating the simulation process in Grasshopper ......................................... 40  
Figure 28 Method for parametric simulations ................................................................ 41  
Figure 29 Part 1 in details .............................................................................................. 42  
Figure 30 Part 2 in details .............................................................................................. 43  
Figure 31 Part 2 in details (continue) ............................................................................. 44  
Figure 32 Ramp-function for likelihood of non-visual effect for overcast sky (D55) ....... 46  
Figure 33 Calculating the circadian threshold ................................................................. 46  
Figure 34 Circadian threshold for overcast, intermediate, and clear skies .................... 47  
Figure 35 Hourly circadian threshold ........................................................................... 48  
Figure 36 Example of a sombrero plot ......................................................................... 49  
Figure 37 March and June hourly results for Top west apartment .................................. 53  
Figure 38 September and December hourly results for top west apartment .................. 54  
Figure 39 March and June hourly results for top east apartment .................................... 55  
Figure 40 September and December hourly results for top east apartment .............. 56  
Figure 41 Comparison between the east and west apartments ...................................... 57  
Figure 42 Average circadian illuminance ...................................................................... 58  
Figure 43 Average non-visual effect for bottom apartment ........................................... 59
List of tables
Table 1 Common photometric units used ......................................................... 15
Table 2 Summary of research papers examining non-visual effects of light ........ 20
Table 3 Summary of research papers examining non-visual effects of light (Cont.) .... 21
Table 4 Daylight hours in each month ............................................................... 32
Table 5 Used material reflectance and transmittance ....................................... 38
Table 6 The simulations in part 3 .................................................................... 45
1. Introduction

Buildings are important in people’s life, as approximately 50% of people now live in cities, and 90% of the time is spent indoors (European Commission, 2003). Reaching comfortable levels in the building interior is affected by many factors that are both physical and psychological. One of these factors is the daylight level. With the general awareness of the benefits of daylight, integrating daylight in buildings is becoming a key design parameter that is constantly considered in the design process and in different disciplines. This includes early design stages where daylight access to buildings is studied, to very detailed analysis stages at the room level. Evaluating daylight in buildings thus differs throughout the different design stages, and is also affected by the building function that is being analysed. The evaluation is usually in reference to set thresholds specified in many building certification systems, and daylight standards. The criteria of evaluation is different from one system to another, but the goal is always the same, which is to provide enough light for comfortable visual conditions.

The link between architecture, daylighting in buildings, and their psycho-physiological effect on individuals has been explored in various research articles. The subject brings together many disciplines namely architecture, neuroscience, environmental psychology, etc., especially when focusing on well-being, human physiology and behavior. Research on the biological effects of light is addressing many variables that architects should consider to be able to design healthy buildings for individuals.

As research advances, the complexities of studying the effects of several variables are overcome through developments in the digital world including various methods for evaluating daylight levels in buildings to mimic the daylight occurrence from the real environment to the virtual (simulated) environment. This includes daylight metrics, such as the daylight autonomy, and useful daylight illuminance, etc. and simulation software such as Diva, Ladybug and Honeybee, and Lightsolve. These methods were first developed to evaluate the daylight quantity in buildings, as the architects’ primary aim was to achieve set illuminance values or visual comfort according to building performance criteria. More recent research focus on the daylight quality instead thus taking visual delight into consideration. Other ongoing research is considering evaluation methods for quantifying ‘circadian daylight’ and its respective effect on the human health and non-visual effects. The three approaches complement each other, and the need to focus on one of them primarily depends on the building function and ambition of the design team.

Attempting to quantify ‘circadian light’ and its associated neuroendocrine and neurobehavioral effect; Biological light response, is a research area that is widely exploited. This includes resetting and shifting the circadian clock which regulates important physiological and behavioral rhythms, such as the sleep-wake cycle, alertness and performance patterns, and core body temperature, thus affecting the daily circadian rhythm of building occupants. Since many factors affect the circadian rhythm, a clear and simplified simulation method is needed to aid designers in evaluating their designs. Many methods were proposed by researches tackling different factors such as the light spectrum, intensity, duration, timing, and history of light. These factors are interconnected, and they are hard to be simulated easily by designers. A simple method should be thus integrated so that the non-
visual effects of light become one of the factors that are considered during the buildings’ design stage.

Since this thesis is addressing a residential building in Malmö, Sweden, the need to focus on the biological light response was deemed necessary. This is first because current daylight metrics focus on evaluating daylight levels at desk height, which is a limited approach and perhaps not even relevant for residential spaces. Since the early and the late daylight exposure in a house affects a person’s alertness and sleepiness levels, either positively or negatively contributing to his/her circadian clock, studying the effect of architectural configurations on the daylight quality and its correspondence on the biological light response is a primary aim of this thesis. This is especially important in Nordic climates, where daylight is scarce in the winter and extremely extended during the summer, making it hard to obtain the necessary day-night cycle for sleeping.

As previous research tackled the relation between light in architecture and how it affects the daily non-visual effects, these are first explained to give an overview of the research findings, as well as the limitations. This is followed by describing the relation between the human health and daylight through photobiology; which describes the interaction of light and humans. This includes the human sensitivity to light, and the different sensitivity to both the visual (perceived) and the non-visual (circadian) effects of light. In addition, it includes the attempts of quantifying the effect of light on the circadian rhythm, and the methods of evaluating it through circadian metrics. One of the methods to be considered is the one proposed by Pechacek, et al. (2008) which was implemented by Andersen, et al. (2011), Mardaljevic (2013, 2012). In these studies, the light spectrum, and the time of occurrence were the two main factors considered. This method is thus proposed to be used in this thesis as it is relatively simple. This may help designers in evaluating the effect of different sky conditions at different times of the year on the biological light response of building occupants.

The third point in the literature is a review of how the photobiology model is converted to a computer simulation script or program, and the current programs used.

1.1 Aims and Objectives:

The main objective of this thesis is to investigate the effect of architectural configurations in terms of biological light response (BLR) in multifamily residential buildings.

The secondary objectives are stated below:

- Evaluate the circadian potential of a space for four critical days in the year; summer and winter solstice, and spring and autumn equinox using ‘circadian illuminance’.
- Assess the combined effect of several factors on the chosen circadian metric (different sky conditions, east and west orientated apartments, storey level, window to wall ratio).

The main research questions of this thesis are:

- What is the effect of the design configurations (east and west orientations, window size, façade inclination, and balcony size) on the average Biological Light response and the circadian potential of the space?
What are the light levels required throughout the day to stimulate the circadian rhythm?
What is the minimum threshold for the circadian illuminance to ensure a high performance space?

2 Literature review

2.1 Photobiology, and daylight in architecture

The design and evaluation of daylight in buildings has become a subject of interest for architects, engineers, and photobiology researchers, and is hence addressed differently in accordance with the set aims and targets. Considering the daylight levels in buildings varies significantly depending on the building type, space function and how it is used, occupancy, aesthetics, energy requirements, in addition to many other factors. Taking these factors into consideration, complex methods aid designers in reaching successful designs combining qualitative and quantitative criteria.

Altering building parameters, such as orientation, window to wall ratio (WWR), shading, etc. affect the daylight level (quantity) and daylight quality in a space. Considering the health effect of daylight in building is therefore quantified through the ‘circadian illuminance’.

Quantifying illuminance levels in a space is carried out by using simulation programs. As this includes many factors and is a complex process in most cases, climate based daylight modelling (CBDM) is used to evaluate buildings at specific locations and times. CBDM is a method to calculate radiant or luminous quantities (such as irradiance, illuminance, radiance and luminance) using sun and sky conditions derived from standard meteorological datasets (Climate-based daylight modelling, 2013). CBDM delivers predictions of absolute quantities (such as illuminance) that are dependent both on the geographical location, the building orientation, and the building's composition and configuration. This simulation method provides a good estimation of whether the space is reasonably lit or not in comparison to reality, and guides designers in their decisions to improve the daylight level in a space.

All simulation tools that are commercially available use ‘photopic illuminance’ in their evaluation criteria. Illuminance is the ‘luminous flux per unit area at any point on a surface exposed to incident light’ (Houghton Mifflin Company, 2001). In this sense Photopic illuminance is the irradiance weighted with the response curve of the human eye vision, while ‘Circadian illuminance’ is the same irradiance but weighted with the response curve of the biological light response (BLR) in the body.

The difference between the photopic and circadian illuminance is that our eye responds differently to the ‘visual’ and the ‘non-visual effects of light through different ‘luminous efficiency functions’. In addition, many metrics and certification systems consider the daylight quantities in buildings through measuring the ‘photopic illuminance’, setting the minimum, maximum and average requirements in some cases. However recent research address the necessity to also consider the ‘circadian illuminance’ because of the health effect of daylight on humans. The term BLR in the thesis is used to refer to the non-visual responses of light, but disregarding detailed light parameters such as the timing of light exposure, and the history of light.
The common daylight metrics consider daylight on a horizontal surface located at desk height, which is 800mm from the floor. However, using this method is more suitable in office buildings, where it is important to achieve a specific daylight level on the working desks. This is not the case in residential buildings, as occupants tend to move a lot, and do not have a fixed view direction. In addition, other subjective factors should be considered such as psychological effect of light, and having a delightful space where occupants would feel comfortable in their homes, which could be a factor contributing to the ‘quality’ of light. This subjective factor is hard to evaluate, as it differs greatly between different genders, cultures, and age groups, but it is a main factor that should not be ignored during housing design.

Evaluating a residential space based on the ‘photopic illuminance’ alone is then not sufficient as it does not necessarily mean that the biological needs are met especially since the visual and the non-visual responses are stimulated through different mechanisms in the eye and brain.

### 2.1.1 Circadian rhythm and its effect on human health (Biological Light Response)

The human physiology, metabolism and behavior is strongly affected and maintained by the daily cycle of day and night. These daily rhythms, called circadian rhythms, are considered as the daily ‘body clock’, as ‘circadian’ is derived from the Latin circa, ‘around’, and diem or dies, ‘day’, so literally translated to ‘approximately one day’. These rhythms however do not exactly last for 24 hours, as the cycles need to be entertained by external stimuli, which is the daily light-dark cycle (Andersen, et al., 2011). The circadian rhythms contribute in many processes in the body, such as the sleep-wake cycle, core body temperature (CBT), alertness and performance patterns, as well as hormone production (Amundadottir, et al., 2013). All these processes could be thus categorized as the biological light responses (BLR) or non-visual responses that are controlled by a different kind of photoreceptor in the eye’s retina in comparison to the human vision.

The BLR is controlled by a non-rod, non-cone photosensitive receptor in the eye called retinal ganglion cells (ipRGCs). This photoreceptor was discovered in 1990s, and was the subject of many researches that addressed the non-visual effects of light. This receptor has a photopigment named melanopsin that is more sensitive to short-wavelength light with a peak sensitivity that is blue-shifted ($\lambda_{\text{max}} \approx 460$-$480$ nm) in comparison to the photopic visual system ($\lambda_{\text{max}} = 555$ nm) which is dominated by the response of cone photoreceptors. The peak sensitivity of the ipRGCs is still not entirely clear, as different researchers documented different findings. The ipRGCs send light induced signals to the suprachiasmatic nuclei (SCN) that has about 50,000 cells (sometimes referred to as the ‘circadian pacemaker’) in the anterior hypothalamus of the brain and receive information exclusively through the eyes (Mardaljevic, et al., 2013) as shown in Figure 1. The SCN then sends signals to other parts of the brain (pineal gland) to control the timing of different BLR that were previously mentioned (Andersen, et al., 2011).
Although the ipRGCs are the primary photoreceptors, the other photoreceptors can also contribute to BLR through different mechanisms. An example is the research that showed that the exposure to short intermittent dim light pulses with wavelengths in a narrow band around 555nm can maintain a sustained non-visual response by stimulating cone photoreceptors (Gooley, et al., 2012). The exact contribution of rods, cones, and the ipRGCs to the non-visual responses is still a subject of ongoing research (Lall, et al., 2010).

As the peak sensitivity of the ipRGCs is shifted towards the blue light, the type of ‘light’ exposure therefore has a major contribution on the BLR stimulation. Research has shown that blue-enriched light improves subjective alertness, performance, mood, and sleep quality in comparison to white light (Viola, et al., 2008). Despite the beneficial effects of exposure to blue-enriched light, it also has shortcomings depending on the exposure time. Various research tackled how the day and night cycle, and consequently the time of exposure to daylight, affect our body and the negative consequences on human performance, alertness and health if this cycle is not maintained (Andersen, et al., 2011). A summary of some hormones that are produced during the day is shown in Figure 2 (Volf, 2013). An example is the melatonin production that peaks at night and decreases during the day which hence regulates the sleep-wake cycle (Lockley & Dijk, 2002, Wehr, et al., 2001). Research has shown that exposure to bright light at night can directly suppress melatonin and stimulate melanopsin delaying the sleep period and decreasing sleepiness in a process named phase delay (noted as PD at nine o’clock in Figure 2) (Wehr, et al., 2001, Cajochen, et al., 2000, Zeitzer, et al., 2000). In addition, daytime exposure to bright light (above 1000lux) reduces sleepiness and improves performance which is known as phase advance (PA in the figure) (Phipps-Nelson, et al., 2003).

Other health related conditions where the circadian clock is not synched are jet lags and shift work disorders. In a jet lag, the body does not immediately reset to the new light-dark cycle as it takes about a day per time zone to be adjusted. However, Jet lags are not as severe as shift work disorders where people work during the night and sleep during the day thus opposing the natural cycle (Lockley, 2009) (Veitch, et al., 2004), as it can result in short-term risk for sleepiness-related accidents and injuries, and longer term risks for health (Mills, et al., 2007) (Viola, et al., 2008). In addition, research has shown that children using luminous displays such as ipads at night delays sleep (Chang, et al., 2014).
From this, it is clear that the duration, intensity, spectrum of light, and time of exposure are main factors affecting the human BLR (Mardaljevic, et al., 2012). These will be elaborated more in details in the next sections.

### 2.1.2 Findings from photobiology

There are five types of photoreceptors in the eye, rods, short (S), medium (M), and long (L) wavelength cones and ipRGCs. For each of these, the spectral sensitivity of the human visual and circadian channel; i.e. how humans respond to different wavelengths of light, are identified as photopic/circadian luminous efficiency functions that are different from each other. Both functions are always used to weight the energy in the electromagnetic spectrum for the determination of luminous intensity. An example is the photopic luminous efficiency function \( V(\lambda) \) which is multiplied and integrated by the spectral power distribution of radiation (SPD) emitted by a source to determine the photopic luminous intensity in candelas of the source. An example is shown below in Figure 3 (Andersen, et al., 2011). Denominations such as D75, D65 & D55 represent standard CIE illuminants with different spectral power distribution in the visible wavelengths as shown in Figure 3.
Figure 3 Photopic ($V(\lambda)$), & circadian ($C(\lambda)$) luminous efficiency function, & SPD of different CIE illuminants

An example for calculating the photopic luminous flux is as follows:

$$\phi_{\text{Photo}} (\text{lm}) = 683 \int_{380\text{nm}}^{830\text{nm}} V(\lambda) \cdot \phi_{\text{radio}}(\lambda) \, d\lambda$$  \hspace{1cm} (1)

Where:

$\phi_{\text{Photo}}$: Photopic luminous flux in Lumens (lm)
683: Photopic luminous efficacy (lm/watt)
$V(\lambda)$: Photopic luminous efficiency function.

$\phi_{\text{radio}}(\lambda)$: Radiometric spectrum over the visible range (Watt).

This equation is different when calculating the ‘circadian luminous flux’, and is as follows:

$$\phi_{\text{Circadian}} (\text{lm}) = 4557 \int_{380\text{nm}}^{830\text{nm}} C(\lambda) \cdot \phi_{\text{radio}}(\lambda) \, d\lambda$$  \hspace{1cm} (2)

Where:

$\phi_{\text{Circadian}}$: Luminous flux in Lumens (lm)
4557: Circadian luminous efficacy (lm/watt)
$C(\lambda)$: Circadian luminous efficiency function.

$\phi_{\text{radio}}(\lambda)$: Radiometric spectrum over the visible range (Watt).

This spectral weighting function is used to derive all units in photometry through the integration explained previously. Examples of the different units used are in Table 1 (Rea, 2013). The most two common metrics are the luminous efficacy, and illuminance. The luminous efficacy is the ratio of the total lumens emitted by a source divided by the wattage needed to emit those lumens.
However this function is not directly used in simulation programs to calculate the photopic and the circadian illuminance values. A simplified equation is used that is explained in details in section 3.5.1.

*Table 1 Common photometric units used*

<table>
<thead>
<tr>
<th>Unit</th>
<th>Abbreviation</th>
<th>Equivalence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminous intensity</td>
<td>candela</td>
<td>cd</td>
</tr>
<tr>
<td>Luminous flux</td>
<td>lumen</td>
<td>lm</td>
</tr>
<tr>
<td>Illuminance</td>
<td>lux</td>
<td>lx</td>
</tr>
<tr>
<td>Luminous efficacy</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

It is worth mentioning that the photopic and the circadian luminous efficiency curves have different luminous efficiencies as shown in Figure 4 (Amundadottir, et al., 2015). These values are the factors (4557 and 683) in equations 1 and 2 respectively. This shows that the ganglion cells are more sensitive to light as a small radiometric flux will generate a high circadian flux in lumens.

![Figure 4 Photopic and circadian luminous efficacy (lm/Watt)](image)

To be able to compare the sensitivity of the two curves, they can be normalized to 1 as shown in Figure 5. The figure shows that the circadian response is clearly blue-shifted with respect to the photopic response. These normalized curves are considered in the simplified equation in section 3.5.1.
2.1.2.1 Photopic Luminous efficiency functions:

Several studies have resulted in different photopic luminous efficiency functions as shown in Figure 6 (Rea, 2013). Despite that, the one in Figure 3 that peaks around 555nm (V(λ)) is the unified one internationally accepted by the CIE in 1924 (Commission International de l’Éclairage, 1924). This function is used by researchers and computer simulation programs. As shown in Figure 6, V(λ) is based on two types of cones, the L and M cones, as the S cones are not largely present in the central fovea, and they respond more slowly to rapid changes in light in comparison to the other two types, but they still contribute to both visual and non-visual responses.

2.1.2.2 Circadian Luminous efficiency function:

Defining a unified circadian luminous efficiency function is an ongoing endeavor, since different researches are producing different functions, even when based on the same data in some cases. The reason for this is that despite the fact that the melanopsin-containing photoreceptors (ipRGC) are the main photoreceptors for non-visual responses (peaking at
480 nm (Berson, et al., 2002, Hattar, et al., 2002)), there are also other mechanisms where light can stimulate different types of photoreceptors to enhance different types of non-visual responses.

Examples of the different circadian luminous efficiency functions are shown in Figure 7 where,

Gall: The function proposed by ‘Gall’ in 2004 (Gall & Bieske, 2004).
C(λ): The circadian function peaking at 480 for the melanopsin-containing ipRGC
Enezi: The function proposed by ‘Enezi’ in 2011 (Enezi, 2011).
V'(λ): The scotopic function.
V(λ): The photopic function.
Rea: is the curve by ‘Rea’ for monochromatic light sources in 2011.

It is worth mentioning that despite the spectral peak of melanopsin that occurs at 480 nm, some curves in Figure 7 have peaks at around 460nm including the one proposed by ‘Gall’ and ‘Rea’. It is also interesting that both ‘Enezi’ (2011) and ‘Rea’ produced their research in 2011 but produced two different functions. This shows that tests are needed in the future to validate and unify one circadian luminous efficiency function (Rea, et al., 2011).

Despite the uncertainty regarding the circadian efficiency function, this thesis is developed considering one circadian functions, which is the one by Rea et al. (2011). The function is based on the acute melatonin suppression data collected independently by Brainard, et al. (2001) and Thapan, et al. (2001), thus it peaks at 460nm as illustrated in Figure 8.
The function proposed by Rea includes sensitivity curves for both monochromatic and polychromatic light as in Figure 9. Similar to the function proposed by Gall (2004), it was based on the work of Brainhard and Thapan (2001) but it was more detailed than the one proposed by Gall, and included more recent research. In addition, considering the function for polychromatic light would be useful in this thesis as the skylight will be later included in the simulation by having its full spectrum. The 'Rea' polychromatic function in Figure 9 (Rea, 2013) was thus proposed to be used in the thesis to calculate the 'circadian illuminance', while 'Gall' will only be used as a reference in some calculations since it was implemented in previous research by Andersen, et al. (2011). The polychromatic function has a negative region between 550 and 730 nm, representing negative spectral sensitivity for polychromatic light in that region (Volf, 2013).
2.1.2.3 Light factors affecting non-visual effects

Different characteristics of light exposure are responsible for stimulating the BLR. Different researchers have identified these characteristics to include the wavelength, intensity, pattern, history, timing and history of exposure. The wavelength is related to the human response to different wavelengths of light, which are the luminous efficiency functions explained in the previous sections. The intensity is related to the effect of light intensities on the BLR, for example the non-linear intensity response relationship between night exposure and BLR. This is hard to estimate especially that there is limited research regarding this response during daytime.

Light pattern is another factor affecting BLR as research has shown that light exposure does not need to be continuous to stimulate BLR. In addition, it is the 24-hour pattern of light and darkness that regulates the biological rhythms, not only daylight. The timing is also important, as the human BLR is regulated by a ‘phase response curve’ which is a curve describing the relationship between a stimulus, such as light exposure, and a response such as a shift in the circadian system (S. Khalsa, et al., 2003). The shift occurs if light exposure in the morning advances the circadian rhythm (shifts it earlier), while late light exposure delays it (Mansbach, 2014). Furthermore the history of exposure also has an effect as non-visual system adapts its response to changes in light intensity over a longer period in comparison to the visual system (Rea, 2013) (Ámundadóttir, et al., 2013).

Addressing all these factors in the thesis would have required a complicated mathematical model that is not yet developed but could be the subject of future research. Instead, the focus in the thesis was on the intensity, and the wavelength.

Researchers, architects, and engineers considered these factors utilizing various methods to study how architecture can also contribute to improving or decreasing the non-visual effects. Some ideas and recommendations in these papers were implemented in this thesis to evaluate and improve the non-visual effect of light.

2.2 Methods examining non-visual effect of light

A summary of the methods and research that examined the non-visual effects of light are summarized in Table 2 and Table 3.

### Table 2 Summary of research papers examining non-visual effects of light

<table>
<thead>
<tr>
<th>Research paper</th>
<th>Research aim</th>
<th>Proposed model</th>
<th>Simulation parameters</th>
<th>Evaluation method</th>
<th>Comparison with field measurements</th>
</tr>
</thead>
</table>
| Daylighting, Artificial Lighting and Non-Visual Effects Study for a Residential Building (Mardaljevic, et al, 2012) | To investigate and explore the applicability of daylighting metrics for residential buildings. Investigate a preliminary metric and method to evaluate the non-visual effects of light. | Software used: Radiance  
History of light exposure: Not considered | A simple ramp function showing the illuminance values to achieve the non-visual effect.  
Instantaneous and cumulative N-VE based on the proposed ramp function. | No comparison |
| Modelling non-visual responses to light: unifying spectral and temporal characteristics in a single model structure (Amundadottir, et al, 2013) | To propose a mathematical model that considers the light intensity, spectrum, duration/pattern, history, and timing.  
To provide a framework that can inform designers of how lighting improves human health. | Software used: Proposed model by the author.  
Reference of the circadian luminous efficiency function: Different based on the time of light exposure and the interaction between multiple photoreceptors. | Simulation time: The model considered multiple parameters but the simulation time was not noted.  
History of light exposure: Considered | The three models considered different factors in details. | No comparison |
Reference of the circadian luminous efficiency function: Different based on the time of occurrence.  
"Linear-non linear- linear" (L-N-L) model by the author. | Simulation time: Annual simulation  
History of light exposure: Considered | Relative N-V response as predicted by the L-N-L model based on illuminance values. | No comparison |
<table>
<thead>
<tr>
<th>Research paper</th>
<th>Research aim</th>
<th>Proposed model</th>
<th>Simulation parameters</th>
<th>Evaluation method</th>
<th>Comparison with field measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metrics of circadian lighting for clinical investigations (Barroso, et al, 2014)</td>
<td>To propose a daylight metric that considers the duration of light (frequency of occurrence)</td>
<td>Software used: Calculations based on the model proposed by author. Reference of the circadian luminous efficiency function: None</td>
<td>Simulation time: Calculations for a three day period History of light exposure: Considered.</td>
<td>Calculating the illuminance values based on four models: magnitude, contrast, clustering and variability.</td>
<td></td>
</tr>
</tbody>
</table>
2.3 Modelling circadian illuminance

As there were many attempts to simulate the circadian illuminance, the aim of this thesis was not to develop a new simulation method, but rather to examine the effect of architectural alterations on the circadian rhythm potential. This section thus examines some limitations of the current simulation tools, and suggestion for a new tool (Lark) to be used is explained.

2.3.1 Current software for daylight simulation

Many software were developed for simulating daylight in buildings. These software use complex ‘raytracing’ methods, where some implement the ‘daylight coefficient method’, and usually have an interface that uses the simulation engine Radiance. The use of daylight coefficient method coupled with Perez sky models have allowed the development of the so-called climate based daylight modelling (CBDM).

The daylight coefficient method is a calculation method in Radiance originally proposed by Tregenza and Waters in 1983. The main concept behind it is to speed up the yearly calculation by producing daylight coefficients, which are simply a matrix of numbers representing the relation between each sky patch and each calculation point in a room. This is achieved by theoretically dividing the hemisphere into disjoint sky segments, then to calculate the contribution of each sky segment to the total illuminance at different sensor points in the building as in Figure 10 through the following equation (Mardaljevic, 1999) (Bourgeois, et al., 2008).

![Figure 10 Daylight coefficient method](image-url)
Dγα = \frac{ΔEγα}{LγαΔSγα} \quad (3)

Where:

Dγα: The calculated daylight coefficient.
Eγα: The total illuminance produced at a point in a room by a small element of sky at altitude (γ) and azimuth (α).
Lγα: The luminance of the sky element.
Sγα: The solid angle of the sky patch.

In most common software, backward ‘raytracing’ is also used as a calculation method. It is dependent on sending rays that start from the eye or analysis position to the surrounding environment until it reaches the light source or is reflected by surrounding surfaces until a number of ambient bounces is reached. An illustration is in Figure 11 where ray A is deflected away from the light source, while ray B reaches the source but through a complicated path (Arvo, 1986).

As the difference between the backward raytracing method and the daylight coefficient method and their relation in current simulation engines might be ambiguous, the figure below is a summary showing the hierarchy of the simulation engines, methods, and some of the available software.
2.3.2 Limitations of current software

Current software that uses Radiance (such as Diva, and Honeybee) represent material through a simplified RGB model (3 channels), but does not include the sky color information in their simulation. The software accordingly only calculates the sky luminance distribution and brightness for the annual and hourly simulations as Daysim converts all the color information as a preprocessing step to greyscale. Since the circadian rhythm potential is readily affected by the change in the perceived colors, using these software without considering the sky color would not have been relevant. Other research such as the one by Amundadottir, et al. (2013) used complex models taking into consideration the whole spectral power distribution of the sky. In this thesis a more simplified model is proposed due to time limitations.

The second limitation of the current software is the lack of circadian calculations based on the circadian sensitivity curves explained in section 2.1.2.

To overcome these limitations, a new Grasshopper plugin named Lark is proposed to be used, in addition to Honeybee, to generate more accurate sky files on hourly basis, and more accurate simulations.
3 Method

This thesis is examining the multistory building in the Greenhouse project in Malmö with latitude 55.6° and longitude of 13°. Quantitative measures were used to evaluate the circadian rhythm potential in some spaces. The quantitative measures encompassed computer simulations using Lark, and Honey bee plug-ins for Grasshopper.

3.1 Context

The Greenhouse building is located in a residential urban context of Augustenborg shown in Figure 13, where the surrounding buildings are 15m in height approximately as shown in Figure 14.

![Building with surrounding context](image)

*Figure 13 Building with surrounding context*

3.2 Building information

The Greenhouse building has a total height of 48m with 14 floors in total. As the bottom three floors are designed as student apartments, they have different floor plans than the rest of the building so these apartments were not studied. Instead, two typical floor plans were considered, the first at a height of 10.5m from the ground level (Fourth level), and the second at the 12th floor (approximately 37 meters from ground) as shown in Figure 14. The two different floors were chosen to investigate the effect of the surrounding context on the circadian rhythm potential.
3.3 Building plan

The typical floor plan consists of three apartments as shown in Figure 15. The apartments are oriented towards the east, west, and south, but only the east and west apartments are considered in this thesis, as the south apartment has different room configurations. Both apartments are exactly offset by $10^\circ$ to the south. Choosing these two directions was logical as Volf (2013) suggested that the BLR would change significantly in them throughout the day.
3.4 Analyzed spaces

In both the east and west apartments, the main focus is to analyze the open space that contains the living room, and kitchen, and faces the exterior sunspace as illustrated in Figure 16. This was motivated by the fact that occupants spend most of their time in this open space when at home in comparison to other spaces. Measuring the ‘circadian illuminance’ in that space would thus give a rough estimation of how different the BLR is in the different apartments, and by how much it changes throughout the day too.

Figure 16 Analyzed spaces in the west apartment (left), full apartment plan (right)

It should still be mentioned that the BLR is mostly affected by the first daylight onset received by humans, which is from sunrise in that case, and is also (forward, or backward) shifted in the afternoon if the occupant is exposed to high illuminance levels (Volf, 2013). This shows that analyzing the bedroom space is important too as it is the first place where occupants receive daylight in the morning, and during the evening in the summer. Since these periods affect the whole circadian rhythm of occupants, it also contributes to their “history of exposure” that was previously explained in section 2.1.2, but this was excluded from the study due to time limitations.
3.5 Computer simulations method

A summary of the complete method used in this thesis is presented in Figure 17. In the method, Rhinoceros was used to build the 3D geometry, which was then connected to the Grasshopper. Three plugins, Lark, Honeybee, and Ladybug were used for the illuminance simulation through different scripts.

![Diagram of the method](image)

**Figure 17 Complete method**

3.5.1 Introducing Lark and its link with Ladybug and Honeybee

Lark is a tool that can be used to generate color information to the Radiance material and sky definitions. This is useful as it adds information to the greyscale sky files from Daysim, where the luminous distribution is maintained hence providing accurate representation of the sun position, but with no color information. Adding color information to the material and the sky files is important as recent studies such as Andersen, et al. (2011) and Inanici, et al. (2015) showed that the spectral content of light at typical interior daylight levels affects human circadian rhythms. Since Lark is used to add color information to sky models, unified CIE models could be thus used as a base for the luminance distribution in the sky over which the color information is added on. CIE skies are standard skies that were developed by the International commission on illumination (Commision Internationale de l'Eclairage, 2016).

The luminance distribution of the sky depends on weather and climate, and it changes during the day as the sun position changes. The standard skies lists a set of luminance distributions, which model the sky under a wide range of conditions, from overcast to clear skies. The ‘Build spectral sky definition’ in Lark was used to generate these skies along with the color information. Figure 18 shows an example of the difference between the standard generated sky files and the one generated from Lark.
Figure 18 Sky file without (top) and with (bottom) color information

Lark can also convert the photopic illuminance to circadian illuminance based on the sensitivity curve from Rea (Rea, et al., 2011) and Lucas (Lucas, et al., 2014). Figure 19 summarizes the Grasshopper components in lark for 3-channels, and the use of Honeybee and ladybug components with it. More details about the components are in Appendix A. As the figure shows, the simulation is first run using Honeybee in Grasshopper to produce the ‘Photopic illuminance’ values. Lark is then used to convert these value to ‘Circadian illuminance’.
Figure 19 Ladybug, Honeybee, & Lark

Details of the tool used and required input

Part 1 (Scripts 1 and 2)

- Ladybug import .epw file
  - Copenhagen weather file was used for the simulation.

- Grasshopper
  - A Grasshopper Script was made to calculate the sky clearance index and sort it into three sky types (overcast, intermediate, and clear).

- Lark convert Spectral Power Distribution (SPD)
  - To write radiance spectral sky channels by loading the sky SPD to generate RGB values for three sky types. The files will be used in the ‘Build Spectral Radiance sky definition’ to generate full sky files for Radiance simulation in Honeybee.

Input needed and the extracted information for the next tool

- Hourly data for the analyzed period
- Global Horizontal illuminance
- Direct Normal radiation
- Diffuse Horizontal radiation
- Solar zenith angle

- Input: ladybug data
  - The sky Clearance index
  - Identifying the hourly sky types for the analysis period through a script.
  - Automatically select a sky SPD for each sky type for all the hours. (Script 1)

- Input: Analyzed values from Grasshopper SPD of three sky types
  - RGB channels for the three sky types

Part 2 (Scripts 3 and 4)

- Honeybee illuminance recipie & simulation
  - To build sky file (with color information).
  - A Grasshopper script was used to automate the simulation process

- Lark 3-channel circadian illuminance
  - To convert the result from Honeybee to circadian illuminance.

Input: Sky types
- Latitude and Longitude
- Month, Day, Hour
- Sky files (then Grasshopper script 2 to save the names to an excel sheet and load them back for the Honeybee simulation)

Input: Sky files
- Analyzed points and view directions
- Month, Day, Hour
- Illuminance values for four points with four view directions

- Circadian illuminance values for four points with four view directions
The ‘3-channel circadian illuminance’ component in Lark uses the following two equations to calculate the photopic and circadian illuminance based on ‘Rea’, et al. (2011) sensitivity curve.

\[ \text{Photopic illuminance} = \eta_p \times (0.2537 \times (R) + 0.6635 \times (G) + 0.0622 \times (B)) \] (4)

\[ \text{Circadian illuminance (Rea)} = \eta_c \times (-0.0405 \times (R) + 0.1532 \times (G) + 0.8873 \times (B)) \] (5)

Where:

\( \eta_p \): The luminous efficacy coefficient in lumen/watt (lm/W) for the photopic illuminance = 179 lm/W. It is calculated by determining the area under the V(\(\lambda\)) curve after normalizing it by 683 lm/W at its peak.

\( \eta_c \): The luminous efficacy coefficient (lumen/watt) (lm/W) for the circadian illuminance = 130 lm/W. The luminous efficacy is the ratio of the luminous flux to the radiant flux or power consumption. It is calculated in this equation by calculating the area under the C(\(\lambda\)) for the Rea sensitivity curve after normalizing it by 683 lm/W at its peak.

R: Red component of the spectrum

G: Green component of the spectrum

B: Blue component of the spectrum

The coefficients next to the R, G and B components for the two equations were derived from V(\(\lambda\)) and C(\(\lambda\)) for the photopic and circadian equations respectively by dividing the curves into three parts at specific wavelengths. An example for deriving the values for the photopic illuminance is shown in Figure 20. Multiplying by the RGB components in both equations is a simplification of equations 1 and 2 instead of multiplying by the full sky spectrum. This is considered as a reasonable approximation to reduce the simulation time. Other research, such as Inanici, et al. (2015) have examined the possibility of multiplying by 9 channels instead of three channels, but this was not covered in the thesis.
Using Lark in this thesis is therefore useful because,
1- Color information of the sky could be added.
2- Circadian equivalent lux according to Rea luminous efficiency curve can be simulated.

3.5.2 Simulation input

3.5.2.1 Analysis period (Link between the analysis period and the sky clearance index)

Due to time limitations, the simulation was run only for four days in the year, which are the spring equinox (21st March), summer solstice (21st of June), autumn equinox (21st September), and winter solstice (21st December). These were chosen as representative periods of how the circadian rhythm could change during different periods through the year. The daylight hours for each of the four days were extracted from the weather file with the aid of Honeybee as in Table 4, and the corresponding sky clearance index was assigned for each hour after calculating it using a Grasshopper script.

<table>
<thead>
<tr>
<th>Month</th>
<th>Daylight Period</th>
<th>Total daylight hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>March</td>
<td>6 am to 18 pm</td>
<td>13</td>
</tr>
<tr>
<td>June</td>
<td>4 am to 20 pm</td>
<td>17</td>
</tr>
<tr>
<td>September</td>
<td>6 am to 17 pm</td>
<td>12</td>
</tr>
<tr>
<td>December</td>
<td>9 am to 15 pm</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 4 Daylight hours in each month

Since the daylight time savings were not considered in the weather file, the time savings were manually implemented in the hourly results presented in the results section (Sveriges Riksdag, 2016). This meant that June and September were forwarded by one hour in comparison to March and December.

3.5.2.2 Sky clearance index

The hourly sky conditions were needed for the daylight hours shown in Table 4. This was required so that a corresponding CIE sky model is chosen from three alternatives (Overcast sky, intermediate, and clear sky). To determine the hourly sky condition for the specified dates, the sky clearance index (e) was chosen as a suitable metric for that (Perez, et al., 1990). The sky clearance index gives a list of values ranging from zero to 11 that represent the transition from a totally overcast sky (zero) to a low turbidity clear sky (11), in other words the sky clearance can be considered as the inverse of the cloud cover index (Yamashita, et al., 2004). The clearance index was calculated using the following equation by extracting the relevant data from the weather file using ladybug and Honeybee, then applying the equation through a Grasshopper script (Perez, et al., 1990).
\[ \epsilon = \frac{(Dh + I)}{Dh + \kappa Z^3} \left/ \frac{I + \kappa Z^3}{I + \kappa Z^3} \right. \]

(6)

Where:

Z: The solar zenith angle.
Dh: The horizontal diffuse irradiance (W/m²)
I: The normal incidence direct irradiance (W/m²)
\( \kappa \): Constant equal to 1.041 for Z in radians.

The results for the evaluated hours using the Copenhagen weather file ranged from zero to eight, and did not reach 11, indicating that these hours did not have 100% clear skies. Perez, et al. was used to differentiate between the overcast and the clear sky, but did not set the index range for the intermediate sky. In this case the hourly sky clearance index was compared with the direct and diffuse irradiation as shown in Figure 21 for March, and the index where the direct irradiation was more than double the diffuse irradiation was the separating point between the intermediate and clear sky, which was 5 in this case, such as at 8 am in Figure 21.

The sky clearance index and the respective sky condition were then categorized as follows,
Overcast sky: zero to one
Intermediate sky: One to four
Clear sky: Four to eight

Figure 21 Deriving the intermediate and clear sky clearance index.
3.5.2.3 CIE sky models

Based on the hourly calculated sky clearance index from the weather file for the four simulated days, the following profiles for the CIE sky types were produced for the simulation for every hour.

![Sky condition for the four months](image)

Figure 22 Sky condition for the four months

3.5.2.4 Sky Correlated color temperature (CCT)

The Correlated color temperature (CCT) is a value allowing to characterize the spectral properties of a light source. The CCT is a ‘specification of the color appearance of the light emitted by a lamp, relating its color to the color of light from a reference source (a black body) when heated to a particular temperature, measured in degrees Kelvin (K)’ (Learning Research Center, 2015). The color of light in reality is determined by how much each point on the spectral curve contributes to its output. Despite that two sources can have the same CCT but with different spectral power distribution, it was still used as a simple method to differentiate between the different sky types. In order to add color information to the sky file, a CCT was chosen for each sky type as previously described in Figure 19.

The chosen values for the overcast and for the clear sky were determined from Inanici, et al. (2015) as 6500K and 25000 K respectively, the value for the intermediate sky however was assumed as an intermediate value between the two (8500K) based on the data in Chain, et al. (1999) as no data could be retrieved for Sweden or Denmark that related the sky CCT with the associated sky types. In addition, a single CCT value was used for each hour in the simulation, despite the fact that in reality, the sky CCT could vary within one hour (Herna´ndez-Andre´s, et al., 2001). More accurate representation for the sky CCT could only be achieved by measuring the sky spectral power distribution (SPD), which is outside the scope of this thesis.
The SPD of each CCT was then generated using the daylight series calculator (Inanici, et al., 2015), where the CCT is input, and the whole spectral distribution curve is generated every 10nm. The graphs show that as the CCT value increase starting from 6500K in the top image to 8500 in the middle, and 25000 in the bottom, the SPD is higher at the blue wavelengths, and is lower at the red wavelengths; i.e. the sky is more blue. These SPD are only considering the sky, and are excluding the sun SPD, to evaluate the effect of the sky solely on the BLR. Including the sun SPD can be implemented in future research.

![Sky Spectral Power Distribution](image)

*Figure 23 Sky spectral power distribution for clear skies (top) intermediate (middle), and overcast (bottom),*

As the SPD for the three sky types is different, the amount of ‘circadian illuminance’ inside the room to achieve a certain BLR would also be different depending on the sky condition.
3.5.2.5 Lark spectral sky
Having the CIE sky type from Honeybee, the corresponding sky CCT, and the global horizontal illuminance, the lark spectral sky component was then used to generate sky files for each hour with color information. A script was generated to automatically select the corresponding CCT for each sky type on an hourly basis. Examples of the generated skies on the 21st of June in Copenhagen are shown in Figure 24. The same skies without the color information are shown in Figure 25 for comparison. Each generated sky for each hour was given a unique name so that it was identified afterwards and loaded in the simulation.

![Images of sky files](image)

*Figure 24 Overcast sky at 5 am (left) Intermediate sky at 12 am (middle) Clear sky at 7 pm (right)*

*Figure 25 Overcast sky at 5 am (left) Intermediate sky at 12 am (middle) Clear sky at 7 pm (right)*

3.5.2.6 Analysis points
Four analysis points were chosen for each space as illustrated in Figure 26, two in the living room, and two in the kitchen area. The analysis points were located based on a possible furnishing plan as follows:
- The living room has a sofa; the analysis points are located at a height of 120 cm.
- The point in the middle of the kitchen is a standing position at a height of 150 cm.
- The point near the kitchen is at a dining table; the analysis points are at a height of 120 cm.

The four analysis points were simulated with four viewing directions. Occupancy behavior and movement were not considered, and hence it was approximated that every view direction will stay the same through the whole day, despite that this is not realistic. There were thus 16 view directions in each apartments, resulting in a total of 64 views in the four apartments.
3.5.2.7 Materials

The materials used in the simulations were only input using their ‘grey’ reflectance value in order to simplify the process. In other words, the effect of wall color on circadian light was excluded from this thesis. One reason for that was the dependency on previous research, as they were all dependent on having “grey walls” in their measurements or calculations. Referring to previous research was important in order to calculate the minimum and maximum thresholds for the circadian rhythm potential to be able to analyze the simulation results in this thesis. Furthermore, having no-colored walls and ceilings reflect a majority of the Scandinavian architecture.

Note that Arsenault, Hebert, Dubois (2012) have indicated that the color of surfaces such as glass may affect the visual perception of a space, making it look more dull or bright, which in turn had an effect on arousal in their research. This shows that any attempt to change the circadian response by manipulating interior colors may result in contradictory psychological effects. A summary of the reflectance values and the glass transmittance values used are summarized in Table 5. These data were provided by the construction company (NCC) involved in the Greenhouse project.
Table 5 Used material reflectance and transmittance

<table>
<thead>
<tr>
<th>Construction</th>
<th>Reflectance/ %</th>
<th>Transmittance/ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walls</td>
<td>70</td>
<td>-</td>
</tr>
<tr>
<td>Ceiling</td>
<td>80</td>
<td>-</td>
</tr>
<tr>
<td>Floor</td>
<td>30</td>
<td>-</td>
</tr>
<tr>
<td>Exterior ground</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td>Surrounding context</td>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td>Multistory building facade</td>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td>Concrete floor and ceiling in the sunspace</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td>Sunspace glass (Single pane)</td>
<td>10</td>
<td>90</td>
</tr>
<tr>
<td>All other glass (Triple pane)</td>
<td>10</td>
<td>59</td>
</tr>
</tbody>
</table>

3.5.3 Running simulations, and documenting output

The simulation method implemented was to study the hourly BLR change according to the hourly change in the sky conditions. It was divided into two parts as shown in Figure 19. Part one was used to generate hourly sky files using Lark and was linked to two scripts, number 1 and 2, while part two was running 3-channel simulations resulting in both circadian and photopic illuminance values from Lark and was linked to scripts 3 and 4.

3.5.3.1 Script 1: selecting hourly CCT values:

In the Grasshopper script, the correct CCT values were chosen according to the sky type in an automated process. This was done by giving a ‘key’ to each sky type (0 for sunny, 2 for intermediate, and 4 for overcast sky), and a script would search for this key and assign the CCT value for each hour.

Since hourly sky files were generated for the daylight hours for each of the four days, a total number of 49 sky files were generated in total. As these hours were simulated for each view direction at the four analysis points (64 points in total), the total number of simulations for the four apartments was 3136 runs. This simulation would have been tedious to run manually, by first loading the correct sky file for the simulated hour, and then selecting the correct analysis point and the corresponding view direction.

To automate this process, four scripts were generated in Grasshopper, and three of them were running simultaneously during the simulation. The reason behind developing these scripts was to be able to run the 3136 iterations without having to manually input any changes in the Grasshopper file. The simulation took 1 minute for each iteration using an Intel(R) Core(TM) i7 (Q720 @ 1.6GHz) laptop, so running 3136 iterations took approximately three days.

3.5.3.2 Script 2: writing the names of the generated sky files in Excel

This script was developed to write the name of the hourly generated sky files for 3136 runs in an excel sheet using the Grasshopper plugin TT toolbox (Food4rhino, 2016). The logic for the sequence of the names was linked to the sequence of simulating the points, and the order of writing the results. This step was only run twice, where the first was generating an
Excel file with 3136 names for the base case, and another had 1565 only for the top apartments that was used for simulating the parametric studies.

3.5.3.3 Script 3: reading the sky names
This script was generated to read the Excel file explained in the second script by connecting its file path from the computer directory. The sequence for reading the file was the same sequence that was used in the second script. Despite that the simulation was possible without this step and the previous one, the two scripts were implemented to ensure that the correct sky file was chosen.

3.5.3.4 Script 4: selecting the correct point and view direction
This script was used to select the correct analysis point and the corresponding view direction. The sequence of the view directions in numbers is illustrated in Figure 26. As shown in the figure, the order of simulating the view direction was always north, west, south, then east, starting with the point on the northern side of the apartment, and ending with the one on the south. This sequence was set for the four apartments, and was run in the following order,
1. Bottom west apartment
2. Bottom east apartment
3. Top west apartment
4. Top east apartment

3.5.3.5 Script 5: saving the results:
To be able to save all the results, a script was generated to automatically save all the results for the 3130 and 1565 simulations in one excel file using the TT toolbox plugin.

The third, fourth, and fifth scripts were all run simultaneously. These scripts were connected to a number slider that ranged from zero to 3130 for the base case, and another one ranging from zero to 1565. Each sky name, analysis point, and view direction had a specific number within the 3130 and the 1565, so that could be selected by the slider. The slider was animated with the correct number of simulations in each case to automate the simulation. A description of how the process was automated in connection with the Honeybee and Lark components is shown in Figure 27,
Figure 27 animating the simulation process in Grasshopper
3.5.4 Parametric simulation

Following the base case simulations, and after analyzing the results, parametric studies were subsequently carried out to investigate the effect of architectural configurations on the BLR. The parametric studies were divided into four parts. This is summarized in the following figure, and the details of the different parts are in Figure 29, Figure 30 and Figure 31.

![Figure 28 Method for parametric simulations](image-url)
The anidolic system is a device that uses non-imaging optics principles to collect sunlight falling on an entry aperture and concentrate it on a smaller exit aperture thus concentrating the light (Compagnon, 1994).
Figure 30 and Figure 31 summarize the simulations carried out in part 2 of the parametric study,

**Part 2**

<table>
<thead>
<tr>
<th>D. No sunspace glazing, with same position of balcony as the base case</th>
<th>E. Move the sunspace &amp; balcony, &amp; reducing sunspace floor area. <em>(To reduce the window area obstructed by the sunspace)</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>F. Change one glazed side to a wall with reflectivity 90%. <em>(To reflect more sun to the interior at the kitchen area)</em></td>
<td>G. Remove the sunspace and balcony. <em>(To increase daylight access to the building)</em></td>
</tr>
<tr>
<td>H. Adding snow A high reflectance ground with 80% reflectivity was simulated for March and December.</td>
<td>I. Changing triple glazing to double. <em>(To increase daylight access to the building)</em></td>
</tr>
</tbody>
</table>

*Figure 30 Part 2 in details*
Part 3 was to combine the best cases from parts one and two, and decide on the necessary parametric changes, which was then conducted in part four. The following table summarizes the studied cases.
Table 6 The simulations in part 3

<table>
<thead>
<tr>
<th>The simulation case</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>N. North window and no balcony</td>
<td>Combining cases G</td>
</tr>
<tr>
<td>O. North and west windows and no balcony</td>
<td>Combining cases G</td>
</tr>
<tr>
<td>P. North and west windows, no balcony, and double glazing</td>
<td>Combining cases G,</td>
</tr>
</tbody>
</table>

Part four investigated the effect of changing the window to floor ratio (WFR) on the average BLR. The position and distribution of the windows were considered whilst choosing the cases. The criteria for evaluating this part was that the average BLR of the space should not be less than 75%, in accordance with a research by Amundadottir, et al. (2013).

3.5.5 Calculating the Biological Light response

As previously described in the simulation input in section 3.5.2, the sky condition for each hour in the four days was calculated and cached. From the literature in Andersen, et al. (2011), it is known that as the sky gets bluer, less illuminance is needed to induce the Biological Light Response (BLR). All calculations and assumptions were based on the research in Andersen, et al. (2011) and will be briefly described in this section. In this thesis, the term Biological Light response is proposed to be used to distinguish this metric from others developed by researchers, as the thesis does not consider the timing of light exposure, the duration, nor the history of light.

To calculate the range of ‘circadian illuminance’ values that induce a certain BLR, the simple nonvisual lighting model based on the dose response curve from the night-time study by Cajochen, et al. (2000) along with the daytime results by Phipps-Nelson, et al. (2003) was used. It should be noted though that the Phipps-Nelson study was conducted with sleep-deprived subjects and dim light, then it is possible that the deduced values are the result of being more sensitive to light in comparison to well-rested subjects or a brighter background. In addition, subjects may react differently to light in the middle of the day as shown by Arsenault, Hebert, Dubois (2012) Although more advanced models were also developed (Amundadottir, et al., 2013), the simple model was chosen to be used as it suited the thesis scope and timeframe (Andersen, et al., 2011).

Based on the conducted research, the simple ramp function model is proposed to be used in the thesis. The ramp function in Figure 32 shows the circadian illuminance values for overcast sky (also represented as CIE illuminant D55) as a product of multiplying the visible range of the sky SPD with ‘Gall’ Luminous efficiency function. It presents a linear interpolation using minimum and maximum illuminance thresholds from 210 lux to 960 lux and the corresponding BLR that also represents alertness from 0% to 100%. It hence expresses that for an overcast sky an illuminance of 210 lux is needed to yield a minimum BLR and the response increases linearly until 960 lux is reached. After this point, adding more light will not yield more BLR. The minimum and maximum values were calculated in Andersen, et al. (2011) and were based on Cajochen, et al. (2000) and Phipps-Nelson, et al. (2003) that resulted in 210 lux and 960 lux respectively. To reach an acceptable BLR in the
examined space, the aim in the simulations was to reach a value of 75% which was an assumed value chosen from the research by Amundadottir, et al. (2013), and was chosen to be used in this thesis. This threshold was not based on research for Sweden or Denmark, but it was still chosen as identifying such a relevant threshold was lacking in research papers.

Figure 32 Ramp-function for likelihood of non-visual effect for overcast sky (D55)

The minimum and the maximum values in the previous ramp function are not applicable for use in this thesis as they are based on ‘Gall’ luminous efficiency function, while this thesis is concerned with the ‘Rea’ function. The same calculation, as in Figure 33, was hence conducted in Grasshopper but using the ‘Rea’ function. The result of the multiplication was generated by calculating the area under the resultant curve, which was represented using a simple script in Grasshopper by drawing a closed curve then using the ‘area’ component. As the result of the multiplication in Figure 33 yielded one value, this number was weighted by the results from Figure 32, to get both the minimum and the maximum values in the ramp function.

Figure 33 Calculating the circadian threshold

Having the SPD of the intermediate and clear skies (as explained in section 3.5.2), the minimum and maximum threshold was then calculated for these sky types as well, and the ramp functions were drawn as in Figure 34,
Figure 34 Circadian threshold for overcast, intermediate, and clear skies

The minimum and the maximum values of the ramp function were plotted hourly for the four days and illustrated in Figure 35, and they will be used in analyzing whether the results of the simulation are sufficient to have a sufficient BLR or not. The minimum and the maximum values and the 75% threshold are used to evaluate the results on hourly basis, and on average for all the hours.

The graphs show for example that at 12:00 the sky is clear in March, intermediate in June, and overcast in September and December. Most of the hours in March were marked as clear, while in June most of them were intermediate. In September and December however the majority of the hours had an overcast sky. The graphs also show that a higher illuminance is needed on an overcast day to provide the same BLR.
Following this, average calculations for the BLR were conducted as follows:
1- The average of the four days in each view direction for the four points in the space.
2- The average of the four directions for every point.
3- The average for all the points with all their directions in the space.
The average result of the whole space was calculated to be used as an indicator for the “BLR potential” of the space. It would therefore show whether the space on average reaches an acceptable BLR corresponding to 75% threshold, and secondly the changes of the different architectural alterations set in the parametric studies.

As all the calculations were performed in Grasshopper, the easiest way to visualize the results was to make the graphs and visualizations directly in Grasshopper.

3.5.6 Reading the output
Since large number of results was simulated, the results were re-read in Grasshopper using TT toolbox Excel reader. This was done in order to draw graphs in Grasshopper, and make graphical representations of the results in plan in the format of a sombrero plot. For more details about the Grasshopper scripting method used, refer to Appendix C.

3.5.7 Results representation in plan
To represent the results visually, a sombrero plot was drawn for each point with its four direction views. An example is shown in the following image, where the average for each direction (the average of the four months) is represented by a quarter of a circle, and the overall average of all directions is written inside the circle. The calculated value is the average Biological Light response (BLR) which could be also an indication of the average
alertness level. The written value is a realistic representation of the average BLR at this point as occupants do not look in one direction all the time.

Figure 36 Example of a sombrero plot
4 Results

This section presents the results of all the simulations starting with the base case, then the parametric simulations with part 1, 2, and then 3.

4.1 Base case

To interpret the base case results, hourly graphs were plotted, and a sombrero plot was drawn with the average BLR at each point and for the whole plan. In Figure 37 and Figure 38, the results of the top west apartment are presented, while the top east apartment results
The detailed results of the bottom apartments are in appendix A, as the difference between the top and bottom apartments was negligible. Therefore only the hourly results of the top apartment are presented in this section. The graphs show the hourly circadian illuminance using the logarithmic scale at each point for the four examined view directions. They also show the hourly sky condition (overcast, intermediate, and clear),
where the grey symbols (circle, square, and triangle respectively) represent the illuminance where the BLR is 0%. The vertical line from these symbols represent the range of illuminance values where the BLR increases from 0% to 100%. As previously explained in section 3.5.5, any values exceeding this range would also result in 100% stimulation of the BLR. In addition, a dashed line in this range was plotted to represent 75% BLR (refer to section 3.5.5). The graphs for June and September were plotted according to the daylight savings time (refer to section 3.5.2). In general, the following points were observed for both the west and east apartments,

- In December, almost all points did not reach the threshold, showing how hard it is for the light to stimulate BLR and alertness in December except in the east apartment in the morning.
- The difference between the four points in each view direction (for example all the points facing west in March) is negligible, and they follow the same pattern.
- All the points in all the view directions in March received illuminance higher than 75% most of the time.
- In June, only the points facing north and west received enough light to exceed the 75% threshold in the west apartment. This was true for the north and east view directions in the east apartment. Despite that, it was generally observed that the number of hours that exceeded the threshold was less than the ones in March.
- In September, only the points facing west in the west apartment, and the points facing east in the east apartment exceeded the 75% threshold for a short period of time. The other directions did not reach the threshold, and in many hours it did not exceed the 0% non-visual effect.

In addition, the following points are more specific to the west and east apartments,

For the west apartment:

- The difference in sky type in one day resulted in peaks such as at 16:00 in June, and 10:00 in December.

- The illuminance levels in the afternoon was generally higher in comparison to the morning in March, June, and September.

For the east apartment:

- Some points showed the variation in direct light patches in the apartment, such as at 07:00 in March for points 1, 2 and 4 facing east, and at 07:00 and 08:00 in June for points 1, and 2 facing east. These peaks were not observed in the west apartment in the evening, despite that in some months similar sky conditions in the morning also occurred in the afternoon, especially during March where the sky type was symmetrical before and after 12 o’clock (refer to section 3.5.2).
- The east on average for all the points, and for the average of the whole plan showed higher illuminance values in comparison to the west, which is also obvious in the sombrero plot in Figure 43 and Figure 44.
Apartment: Top West

March

Circadian Illuminance (Lux)

North

Circadian Illuminance (Lux)

West

South

Circadian Illuminance (Lux)

East

June

Circadian Illuminance (Lux)

North

Circadian Illuminance (Lux)

West

South

Circadian Illuminance (Lux)

East

Sky condition and respective circadian threshold

- Overcast sky (190-570 lux)
- Intermediate sky (156-715 lux)
- Clear sky (105-483 lux)

75% of the maximum circadian threshold

Figure 37 March and June hourly results for Top west apartment
Figure 38 September and December hourly results for top west apartment
Figure 39 March and June hourly results for top east apartment
Figure 40 September and December hourly results for top east apartment
To easily compare between the values of the east and the west apartments, all the points for all view directions were plotted in Figure 41 which gives an overall view of the daylight pattern in the two apartments. The graph shows the simulated daylight hours for the four months, and the corresponding circadian illuminance. The results during March and June exhibit opposite patterns before and after 12:00; in March in the east apartment the illuminance is higher in the morning then decreases, while in the west apartment it is low in the beginning of the day then it increases, which was an expected result since the sun moves from east to west during a day. This is not apparent in September and December as the two apartments follow almost the same pattern throughout the two days but with different illuminance values. In December, the peak in the east apartment in the morning is more apparent at 10:00 in comparison to the west apartment where there is no peak in the afternoon due to cloud cover. The average circadian illuminance for the four months is plotted in Figure 42. The graph shows a reduction of 56% from March to June, 65% from June to September, and 68% from September to December. From this, the difference between June and December is a reduction of 95% in the average circadian illuminance, which in itself shows how difficult the daylight conditions are in southern Sweden during December.

![Figure 41 Comparison between the east and west apartments](image)
The graph in Figure 42 also shows some differences between the east and the west apartments specifically during March and June, which is primarily because the sky condition during each day is different before and after 12pm, accordingly each apartment receives a different amount of daylight.

From the illuminance values, the average BLR and alertness was calculated and plotted on the sombrero plot.

**Sombrero plot:**

The average BLR for every point and every view direction is shown in Figure 43 and Figure 44. Taking every point separately, the results show that the best view direction in any apartment is always towards the window; facing east in the east apartment, and facing west in the west apartment. The average BLR for the four view directions at each point (the values inside the sombrero plot) was calculated as in reality a person does not look in only one view direction, but moves around the space constantly. Considering the top apartments, points 1 and 2 in the west apartment, and 5 and 6 in the east have a difference in the average BLR of 3%- 4%. At these two points, any direction facing away from the window has the same BLR. Points 3 and 7 have the highest BLR as they are the closest to the window. Points 4 and 8 have the lowest as it is the most distant from the windows.

The bottom apartment have a lower BLR in comparison to the top apartment, but the difference between them is negligible (approximately 1%-2%). This average was calculated to give an approximate estimation of whether the apartments reach the circadian threshold of 75% or not. In the base case, the maximum average BLR is 52% in the top east apartment. The reason for this could be explained through Figure 45 which shows the average BLR for each month separately for the four apartments. It is apparent that only March reaches 75%, possibly due to the fact that it was input as the most month with clear sky. In June, March, and September, the difference between the average BLR was not significant. However in December, there is a difference between the four apartments, possibly due to low sun angle.
Figure 43 average non-visual effect for bottom apartment

Figure 44 average non-visual effect for the top apartment
As the average percentage of BLR for December was really low, an investigation was made to compare the effect of different sky conditions (clear, intermediate, and overcast) on the December results. The reason for this was to check whether changing the sky conditions, and having a clear day in December would result in a suitable BLR of at least 75% or not. The results in Figure 46 show both the circadian illuminance (solid line) and the average BLR (dotted line). On average, the clear sky resulted in higher results in comparison to the intermediate and the overcast, yet still all points did not reach 75% average BLR. The difference between the clear and intermediate skies was between 7-11%, while the difference between the intermediate and overcast was around 4-5%. 

Figure 45 Percentage of BLR for each month separately
From this, the sequence of the parametric studies was chosen to examine possible configurations in the building to improve the average BLR especially in December. In addition, the average BLR was calculated with and without December, since it was concluded from the base case that adding December greatly reduces the average, and that even with a completely clear sky the BLR does not reach 75%. However it is possible that the 75% threshold is too restrictive as it is known from direct experience that a beautiful winter day in Sweden would bring a cheerful biological experience.

4.2 Parametric simulations

4.2.1 Part1

The results for part 1 which investigated different parameters and their effect on December is presented in Figure 47. The plots show the average BLR of the whole apartments (east and west) in every direction, as well as the average for all the view directions (written in the center of the sombrero plot). The results show that with maximizing the WFR, the average BLR increased from 24% and 32% in the west and east apartments (Figure 45) respectively to 42% and 48%, yet still it did not reach 75% in December. Removing the balcony increased the averages to 54% in the west, and 60% in the east apartment in comparison to just changing the WFR. Adding an Anidolic system did not improve the average BLR, but resulted in a more uniform distribution of light in the four view directions in comparison to the simulated cases A and B.
Figure 47 Average BLR for December in top apartments

From this, it was decided that the rest of the parametric studies will be evaluated by averaging the results with and without December. This was because it was noticed that adding December in the calculations significantly reduced the BLR as the illuminance values were always low.

4.2.2 Part 2

All the results of part 2 for the top east and west apartments are represented by sombrero plots in Figure 48. The sombrero plots in this case has two circles. The inner circle represent the average BLR in the four view directions including December in the calculation, while the outer circles excludes December. The details of each simulated case in comparison to the base case is as follows:

D. No sunspace: Removing the glass part of the sunspace did not improve the results, which is due to the fact that the balcony was still shading the glass areas.

E. Moving the sunspace: it still did not improve the average BLR similar to case D.

F. Adding a reflecting wall: The wall blocked more solar irradiation in comparison to the base case, so the average BLR was reduced in the west, south, and north in the west apartment, and in the north and east in the east apartment. As shown in
Figure 49 that summarizes the average BLR for the whole apartments, the average BLR was reduced by 5% in the west, and 2% in the east, noting that the difference was not equal on both sides.

G. Removing the balcony: The average BLR increased in all view directions by 8-10%.
H. Adding snow: The average BLR did not increase in all directions.
I. Double glazing: Increased the BLR in some view directions but only by 4-6%.
J. Northern window: Increased the average BLR by 5-7% resulted in more uniform lighting in the north and west directions in the west apartment, and in the north and east apartments in the east.
K. North and west windows: The result for the west apartment was not different, while for the east it increased in the north, east and south when including December, and in all views when excluding December.
L. West and two north windows: resulted in more uniform results; different view directions had similar average BLR.
M. South orientation: the average BLR increased in all view directions, but the total average was 52% which was 2% higher than the west apartment, but was the same average as the east apartment. More details about the difference between the east, west, and south apartments are in the description of Figure 50.

Excluding December in the average BLR increased in most view directions by a maximum of 10%. Some view directions exceeded the threshold of 75%, but a single view direction is not a sufficient indication as occupants are constantly moving in the space.

![Figure 48 Detailed results for part 2 with and without December](image)
All the simulated cases on average for the east and west apartments still did not reach 75% threshold as shown in Figure 49.

The best simulated cases with the highest increase in the average BLR are G (removing the balcony), followed by J (adding a northern window) and I (double glazing), then L (west window and two northern windows) and K (North and west windows).

Figure 49 Average of west and east apartments with and without December

Figure 50 shows that the south oriented apartment still did not reach 75% threshold. It had similar pattern in the four view directions as the west apartment. The only month that showed higher average BLR in comparison to the west and east apartments was December, which is due to the low angle of the sun, and the fact that the sun in December is mainly present near the south orientation. An overall observation from this graph was that March had very close results in the four directions in the three apartments. This is explained by the fact that the BLR was calculated as 100% after the illuminance reaches the maximum threshold (Refer to section 3.5.5), which was the case in March.
The results in Figure 48 and Figure 49 were used as a guide for the parametric simulations in part 3 as follows:

1. Simulation G (removing the balcony) was in all the simulations as it had the highest impact on improving the BLR.
2. Simulation L (west window and two northern windows) was not included in part 3 as it was thought that it would not be the best option for the space from an architectural point of view.
3. The difference between J (northern window) and K (north and west windows) was investigated.
4.2.3 Part 3

Combining the best simulation results from part 2 together radically improved the average BLR. The details of the results are presented in Figure 51, and the summary is in Figure 52. The results in comparison to the base case are as follows:

N. North window and no balcony: The results varied in the different view directions from approximately 50% to 75% including December, and from 60% to 81% excluding December, which shows great improvement in comparison to the results of the base case. The west view direction in the west apartment and the east direction in the east apartment reached 80%.

O. North and west windows and no balcony: The results were less than simulation ‘N’, as the west window is mostly shaded by the sunspace and the balcony. The values ranged from approximately 50% to 63% including December, and from 60% to 80% approximately excluding December.

P. North and west windows and double glazing: The values improved more in comparison to simulations ‘N’ and ‘O’. The results of the west and east apartments were almost symmetrical as shown in Figure 51, but the total average values were different as shown in Figure 52. The values ranged from 55% to 75% including December and from 65% to 82% excluding December.

The average of the four view directions of every case is presented in Figure 52. All the simulations in part 3 are very close to the 75% threshold. Simulation ‘N’ (north window and no balcony) almost reached 75% threshold when excluding December. Simulation ‘O’ (North & west window & no balcony) was the lowest of the three simulations, while Simulation ‘P’ was the highest, with the east apartment having an average of 74%, and the west was 73% when both excluded December. The detailed values at every point and for every view direction for simulation are shown in Figure 53.
The plan in Figure 53 shows that the two points near the window reach an average of 72-74% which is almost the required threshold considering that the simulation in radiance have a marginal error every time the simulation is run. The two points at the living room are also within the acceptable threshold. The point in the kitchen however has an average between 56-58%, but has high BLR in the north and west directions in the west apartment, and in the north and east in the east apartment.
5 Discussion

The presented results give ideas of how the four points that represent critical areas in the two apartments receive enough ‘Biological light response’ representing alertness levels. As the results were compared to a calculated range of values where the BLR range from zero to 100%, the set threshold of 75% was arbitrarily chosen. Since most of the simulations of the parametric studies (part 1 and 2) and the base case do not easily reach this threshold, the question of whether this threshold is applicable to the Swedish weather or not should be further examined not only through qualitative methods, but also through qualitative measures through questionnaires and surveys, as well as medical studies. An assumption could be made that the threshold could be lower to approximately 50% based on the results from December, as occupants feel alert when the sky is clear in December. This could be because of biological factors in people living in Sweden such as skin color and adaptation.

One of the key parameters that affected the simulation results was the chosen CCT values for the three sky types. As these values excluded the sun component, and only considered the sky, the simulation showed that the more blue the sky gets (and the higher the CCT values) the better it is for the average BLR. This was clearly evident after simulating December using three assumed sky conditions (clear, intermediate, and overcast). The sun was excluded in the CCT assuming that the overall sky color reaching the apartment would still be more blue in comparison to the warm sunlight from a clear sky for example, except when there is a direct light patch entering the apartment. This simplification was made, but further investigation is needed to check how different sun positions would affect the overall sky color, and whether in this case inputting it as a number such as the sky CCT would be suitable or not.

The following points are the discussion of the conducted simulations:

5.1 Base case

The east apartment had higher average BLR in comparison to the west apartment. This was because of observed high illuminance peaks in the east apartment that was not observed in the west apartment, mainly because more clear sky condition was observed in the morning in comparison to the afternoon in the sky profiles used for the simulation calculated from the weather file. Another reason is the unequal number of hours before and after 12:00 hours.

But this was also observed with symmetrical sky condition before and after 12:00 hours such as the case in March. This was not due to the difference in the context in the east or the west, nor because of the shape of the rest of the building as these factors were examined in separate simulations, and still the east apartment had higher average in comparison to the west. The reason for the difference could be due to how the sun is interpolated in the simulation, so that the exact sun position in the east direction in the morning is not exactly repeated again in the afternoon in the west apartment. It could be also due to the difference in the division of the sky patches in the east in comparison to the west. The results are very sensitive to small differences because only four points were considered, if more points were simulated the average would be different, and the difference between the east and the west could be less.
When plotting all the values for the east and the west apartment in Figure 41, the values in March and June follow opposite patterns for the east and the west; In March it is higher in the east in the morning, and higher in the west in the afternoon for example, because the sun path causes direct sun in the apartments. The results for September and December did not exhibit this trend, as all the results followed the same pattern for the east and west but with different illuminance values. This is explained by the sun path as well, as the sun does not reach the apartments directly, so the results plotted are mainly dependent on the diffuse light rather than the direct light.

It is worth mentioning that the timing of sun exposure in the apartment is important. As the circadian system in the body is boosted by morning sun exposure, it is better to receive high illuminance values in the morning as it will increase the alertness level throughout the day. In addition, getting exposed to high illuminance levels in the afternoon will negatively affect the sleep quality. Furthermore, to benefit from the low sun angles during the winter, it is better to orient the bedroom and the main living spaces towards the east and south directions.

5.2 Parametric simulations

5.2.1 Part 1

The results show that even with full glazed apartments, the average BLR does not reach 75%. The main reason for this was the small number of daylight hours in December that result in insufficient daylight to the east and west. This could be improved by orienting the apartments more towards the south. One solution could be to exclude December in the total BLR calculation, and to propose recommendations to improve the average BLR in the rest of the year. This could be a reasonable explanation considering that people adapt to December weather, and that they are also exposed to higher illuminance values when they spend time outdoors.

The results of the anidolic system did not readily improve the results, which is mainly because Daysim has some limitations regarding such simulations. More investigations could be made in the future examining different geometries and dimensions of the anidolic system and its effect on increasing the illuminance level in the apartment.

5.2.2 Part 2

The highest BLR was from simulating the building without the balcony, and changing the triple glazing to double glazing. Removing only the glazed part of the sunspace did not have large effect as expected. One reason is that the sunspace was blocking only one point in the space, which was the one near the window in the dining area. Another reason was the high transmittance value used for the sunspace glazing that it was still transmitting a lot of light to the apartment, so the results are within the program’s simulation error.

Adding snow in March and December did not affect the results either, which could be because of using backward raytracing which means that the rays from the analysis points do not reach the ground surface especially in the top apartment.

5.2.3 Part 3

The best simulated case with the highest BLR was with north and west window and with double glazed windows instead of triple glazing. This case approximately reached 75% on
average excluding December. If the 75% threshold is considered, then the recommendation for this apartment would be to have a WFR of 29% approximately, no balcony, and to use double glazing instead of triple glazing. Using double glazing would however have negative impacts on the energy use, and could not be used as a recommendation for the Swedish weather. A balance is then needed between the allowed BLR threshold and the type of glass used that would be energy efficient too.

If triple glazing would be used, higher WFR should be used, but this would have been practically impossible to implement as it would affect the privacy of the people using the apartment. However, if the threshold is reduced to 50%, using triple glazing could be a recommendation in this case.

All the points excluding the point in the kitchen had average BLR very close to 75%. The point in the kitchen had low average BLR because it is the most distant from the window. This brings to the conclusion that a distance of approximately 3 meters (location of P2 in the living room) is convenient for reaching sufficient circadian illuminance threshold. This is highly dependent on the window distribution and the geometry of the space so it cannot be used as a general conclusion in other cases. Further investigation on this could be made with more points offset at different distance from the main walls, and different window configurations to be able to derive more reliable conclusions.
6 Conclusion

Daylight in buildings, specifically the light and dark daily cycle, has a major role in affecting the human biological light responses (BLR) and the circadian rhythm. Design methods should therefore integrate this factor especially in residential buildings rather than just relying on certification systems to evaluate the space performance. Quantifying the negative effects on BLR that could result from design decisions is therefore needed to build biologically 'performing' designs. This thesis is important as it studies the effect of different architectural alterations on the 'circadian illuminance' received at vertical eye level, and the corresponding BLR. This was motivated by the fact that alertness levels are readily affected in Sweden during overcast conditions, which affects the overall performance levels of individuals.

As different methods were developed in previous research, the thesis tackles one main factor that affects the BLR, which is the sky spectrum and color. The analysis was performed using 'Lark' by assigning a reasonable sky Correlated Color Temperature (CCT) value to three sky conditions (Clear, intermediate, and overcast). Despite that this method produced reasonable results, other accurate methods should be applied if BLR is evaluated in practice for example, as the same CCT values could refer to different spectrum distribution.

Simulating the east and west apartments showed that the east apartment received higher average BLR in comparison to the west. It should not however be derived as a conclusion that the east apartment performs better as the results are dependent on the weather conditions of only four days. In order to derive more reliable conclusions, simulating one point in the middle of the apartment but using more days (or an annual simulation) would be suitable for deriving such a conclusion.

Simulating the base case entailed the comparison of two floors which are the 4th and the 12th. The difference between the two was not significant, as the bottom apartments were on the fourth story, so they were not affected by the surrounding context. Yet still in both floors, all apartments did not reach a threshold of 75%, instead they reached an average of 50% including December, and approximately 60% excluding December. Determining this threshold needs further investigation especially since most of the parametric studies did not reach it, and would probably require questionnaires, surveys, and medical investigations. In addition, it would possibly be a reasonable assumption to exclude December in the average BLR as the small number of daylight hours make it hard to reach high BLR values in December.

The results show that the more clear (and blue) the sky gets, the higher the BLR values. This was previously validated in the literature, showing that the method implemented in the thesis is viable and would be applicable for further developments in the future.

There were five major improvements that could positively affect the BLR in comparison to the base case, and they are summarized as:

1. The fist was removing the balcony completely (8-10% increase in BLR).
2. Adding a window in the north direction (5%).
3. Using double glazing instead of triple (4-7%).
4. Having a west window and two northern windows (2% increase in the east apartment).
5. Having windows on the north and west sides (2% increase in the east apartment).

The recommendation after conducting all the parametric studies considering both the average BLR and architectural factors was to have a north and west windows in the west apartment, and north and east in the east apartment, remove the balcony, and replace the triple glazing with double glazing. This would not have been the most energy efficient solution, as double glazing would increase the energy use in the apartment, but the balance would be decided by the architect taking all the points in consideration.

In the future studies, more simulations covering more days in the year should be considered to derive more reliable conclusions as it would point out problematic periods throughout the whole year. Furthermore, including the behavior of occupants in the space instead of averaging the results of each direction separately would definitely be an improvement to the current simulated model. Lastly a more detailed model overcoming the limitations of the simple method used in the thesis (such as the history of the light exposure, and the sun CCT), should be considered in the future. More research would be then needed to develop some design guidelines for architects targeting the improvement of the average BLR.

Finally, in conclusion, considering both the visual and non-visual effects of light during the design of residential buildings, would improve the overall design quality, and the health of individuals.
7 Summary

Daylighting in buildings is a broad research topic that links architectural design with building engineering, and considers human physiology and behavior. Past research focused on the visual effects of light while more recent research addresses non-visual effects of light. This recent research is interested in how light affects the human health, specifically the circadian rhythm that controls many hormones and functions in the human body on a daily basis. Considering this topic in residential buildings is a crucial aspect as humans are subject to their first and last light exposure at their homes, which would have an important impact on the daily circadian rhythm. Evaluating this in a residential building is however a very complex process as many variables contribute such as wavelength or spectrum distribution, time of exposure, and history of light. The method used in this thesis considers the daylight spectrum, and time of exposure as a simple method that would be indicative of the space performance in terms of the biological light response.

To evaluate the considered building, four days (two equinoxes and solstices) were simulated with their respective sky conditions for an east and a west-facing apartment. The sky conditions were calculated from the weather file data using a ‘sky clearance index’ equation. Four critical points were analyzed that represent the most common seating and standing positions in the two apartments. Each point was analyzed by simulating the vertical illuminance reaching the eye in four orientations (north, south, east and west).

The Grasshopper plugin, ‘Lark’ was used in this thesis, in addition to Honeybee and Ladybug to perform these simulations. The two main reasons for using Lark is first to add color information to standard CIE sky files by representing each sky condition (overcast, intermediate, and clear) by a corresponding Correlated Color temperature (6500, 8500, 25000 respectively). The second reason is to be able to convert the ‘photopic illuminance’ that is used in all simulation software to ‘circadian illuminance’ as the human sensitivity to the non-visual response of light is shifted towards blue wavelengths in comparison to the photopic sensitivity curve.

Several calculations were carried out to determine the minimum and maximum required ‘circadian illuminance’ values and the corresponding percentage of non-visual effect or alertness. A threshold of 75% was arbitrarily selected based on previous research and was considered the minimum average of the whole space. The results showed that the base case and most of the other cases did not reach this average threshold of 75% when averaging the four days, but it was reached when taking the average of March and June. The average threshold was not reached in December at all even with a fully glazed apartment, primarily because of the sun position in December in relation to the east and west apartments.

After several simulations, the best simulated case was a north and a west-oriented window without balcony and sunspace, and with a double glazed window. The major improvement in the average non-visual effect was after removing the balcony, accordingly maximizing unobstructed glass areas is therefore a recommendation in Swedish climatic conditions.
8 References


Ámundadóttir, M., Lockley, S. & Andersen, M., 2013. *Integrating non-visual effects of light into lighting simulation: Challenges ahead*. Krakow, Poland, s.n.


9 Appendix A

Scripts were generated in Grasshopper linking Ladybug, Honeybee, and Lark. The exact components in each of these are presented in the following figures.
10 Appendix B

Base case results for the bottom apartments:

Apartment: Bottom West

March

![Graphs showing circadian illuminance for different directions (North, West, South, East) with timelines for March and June.]

June

![Graphs showing circadian illuminance for different directions (North, West, South, East) with timelines for March and June.]

Sky condition and respective circadian threshold:
- Overcast sky (190-670 lux)
- Intermediate sky (150-715 lux)
- Clear sky (105-483 lux)

*Figure 54 March and June Hourly results for bottom west apartment*
Figure 55 September and December Hourly results for bottom west apartment
Figure 56 March and June Hourly results for bottom east apartment
Figure 57 September and December Hourly results for bottom east apartment
Rhino is a 3D modelling program that “can create, edit, analyze, document, render, animate, and translate NURBS curves, surfaces, and solids, point clouds, and polygon meshes” (https://www.rhino3d.com/features). NURBS are “Non-Uniform Rational B-Splines, are mathematical representations of 3-D geometry that can accurately describe any shape from a simple 2-D line, circle, arc, or curve to the most complex 3-D organic free-form surface or solid”. (https://www.rhino3d.com/nurbs)

DIVA-for-Rhino is a highly optimized daylighting and energy modeling plug-in for the Rhinoceros - NURBS modeler. The plug-in was initially developed at the Graduate School of Design at Harvard University and is now distributed and developed by Solemma LLC. (http://diva4rhino.com/)

Grasshopper® is a graphical algorithm editor tightly integrated with Rhino’s 3-D modeling tools. Unlike RhinoScript, Grasshopper requires no knowledge of programming or scripting, but still allows designers to build form generators from the simple to the awe-inspiring. http://www.Grasshopper3d.com/
12 Appendix D

The logic for saving the results to excel:

Figure 58 shows the order of saving the results for March in grey with the exact sequence of the rows and columns.

As the image shows, the results of the first view direction is first saved for the daylight hours in one month in the first column, followed by the second view direction in the second column, and so on. This is first done for the four apartments (64 view directions) for one month, then the whole sequence is repeated again for the other three months. In order to do that, the correct number of the column and the row needed to be automatically loaded to TT toolbox every time the simulation is run, which was possible with the Grasshopper component ‘cross reference’.

The logic for re-reading the results in Grasshopper:

To be able to understand how the data were re-read in Grasshopper, some terms in Grasshopper should be first explained. As data is loaded in Grasshopper, a big “list” of numbers is generated and Grasshopper retains the order in which they were written by forming a data “tree” with several “branches”. A data tree is an organized structure for storing a lot of data in sub lists. As shown in the image below, there is a main path {0} that could be considered as the tree trunk. The main path then has several ‘branches’ or sub lists that inherit the index of the parent branch, and add a new sub index, such as {0;1}. In each branch there is a number of data (N=5 for example).
As large data were read from excel, they also inherited a data tree structure according to the way they were written. As each number has a path index, and a sub-index, the whole path could be separated by using the ‘split tree’ component in Grasshopper, or even a number in a specific path if its order in the list is known by using the ‘list item’ component. Figure 60 shows how the sub index of the list was input, in this case the sub index was input separated by a comma, which means that all the numbers in these paths will be separated into a new list. These data could be then averaged, and plotted on a graph.